4.4 Electric and Magnetic Fields

This topic covers Coulomb's law, capacitors, magnetic flux density and the laws of electromagnetic induction.

This topic may be studied using applications that relate to, for example, communications and display techniques.

This unit includes many opportunities for developing experimental skills and techniques by carrying out more than just the core practical experiment.

Candidates will be assessed on their ability to:

92 understand that an electric field (force field) is defined as a region where a charged particle experiences a force

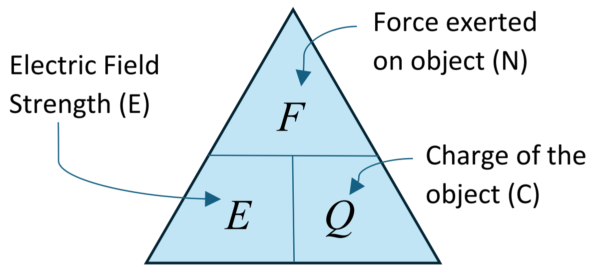
An electric field (a type of force field) is "*a region where a charged particle experiences a non-contact force*" (i.e. where a charged particle is accelerated)

Electric fields can be represented as vectors and as diagrams containing field lines:

- Distance between field lines represents the strength of the force exerted by the field in that region
- Direction of arrow shows show the direction that a force acts on a mass a.k.a the direction of acceleration of a mass placed in the field

A *force field is an area in which an object experiences a non-contact force*
An *electric field is a force field in which charged particles experience a force*

93 understand that electric field strength is defined as $E = \frac{F}{Q}$ and be able to use this equation

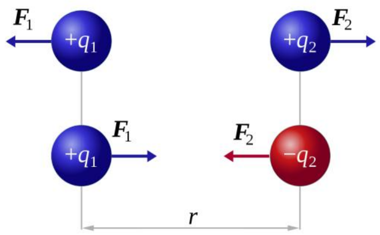


Electric field strength (E) is ***"the force per unit charge experienced by an object in an electric field"***
This value is *constant in a uniform field*, but *varies in a radial field*

94 be able to use the equation $F = \frac{Q_1 Q_2}{4\pi\varepsilon_0 r^2}$ for the force between two charges

Coulomb's Law states that:

"The electrostatic force between two point charges is proportional to the product of the charges and inversely proportional to the square of the distance between them"



$$F = \frac{Q_1 Q_2}{4\pi\varepsilon_0 r^2}$$

Where ε_0 is the permittivity of space and r is the distance between the charges

If charges have the same sign, the force will be repulsive	If charges have opposite signs, the force will be attractive

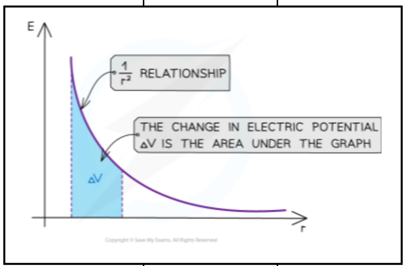
The $1/r^2$ relation is called the 'inverse square law'
This means that if the distance between two charges **doubles**, r becomes $2r$

Therefore, $1/r^2$ becomes $1/(2r)^2$, which is equal to $1/4r^2$
Hence, the electric force between the two charges **reduces** by a factor of **four**

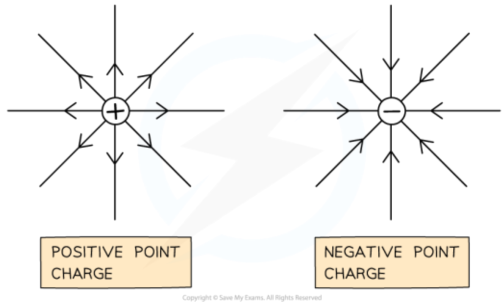
95 be able to use the equation $E = \dfrac{Q}{4\pi\varepsilon_0 r^2}$ for the electric field due to a point charge

A radial electric field is formed due to a point charge

***E*lectric field strength at a point** describes how much electric force is experienced by a point charge at that point



$$E = \frac{Q}{4\pi\varepsilon_0 r^2}$$



where Q = the point charge producing the radial electric field (C), r = distance from the centre of the charge (m) and ε_0 = permittivity of free space (F m^{-1})

The $1/r^2$ relation is called the 'inverse square law'
This means that if the distance between two charges **doubles**, *r* becomes *2r*
Therefore, $1/r^2$ becomes $1/(2r)^2$, which is equal to $1/4r^2$
Hence, the electric field strength between the two charges **reduces** by a factor of **four**

96 know and understand the relation between electric field and electric potential

- A positive test charge has electric potential energy due to its position in electric field
- The amount of *electric potential energy* depends on:
  1. The magnitude of charge
  2. The value of the *electric potential* in the field
- The relationship between the electric field strength and the electric potential is:

  "Electric field strength is proportional to the gradient of the electric potential"

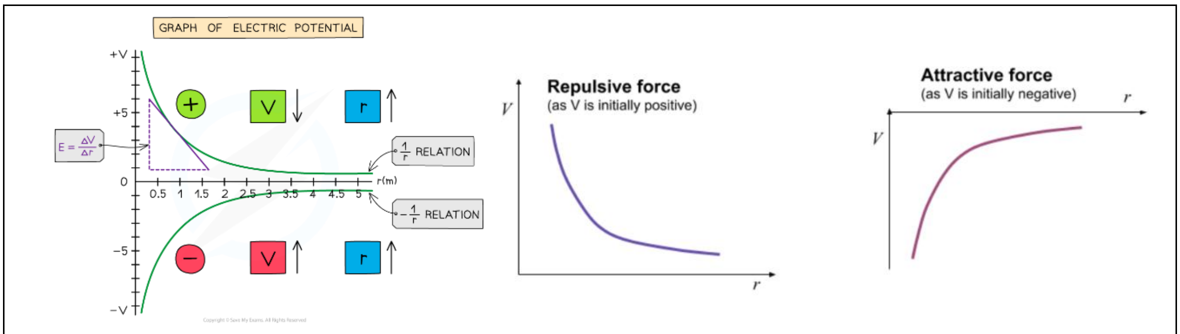
Electric potential (V) at a point is

"the potential energy per unit charge of a positive point charge at that point in the field"

- Absolute electric potential is greatest at the surface of a charge
- Electric potential at infinity is zero
- As the distance from the charge increases, the potential decreases

Whether the value of the electric potential is negative or positive depends on the sign of the charge (Q)

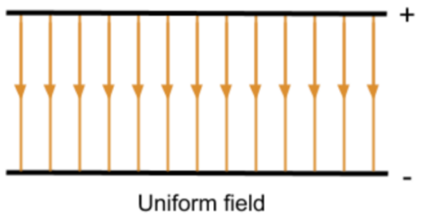
- When the charge is positive, potential is positive and the charge is repulsive
- When the charge is negative, potential is negative and the force is attractive



97	be able to use the equation $E = \frac{V}{d}$ for an electric field between parallel plates
98	be able to use $V = \frac{Q}{4\pi\varepsilon_0 r}$ for a radial field

97

A uniform electric field is formed between a pair of parallel plates



Electric field strength (E) between parallel plates can be calculated using:

$$E = \frac{V}{d}$$

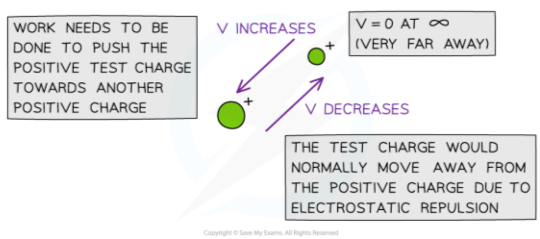
98

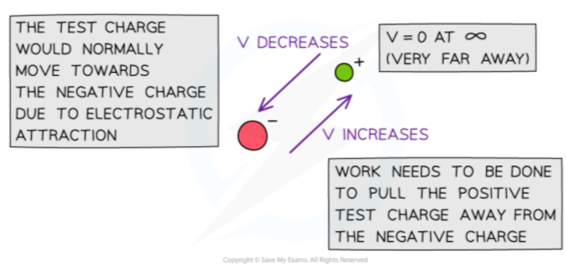
The **electric potential at a point (V)** is defined as:

"The work done per unit charge in bringing a positive test charge from infinity to that point"

- Positive around an isolated positive charge
- Negative around an isolated negative charge
- Zero at infinity
- Electric potential is a scalar quantity

$$V = \frac{Q}{4\pi\varepsilon_0 r}$$





Unlike the gravitational potential equation, the electric potential can be positive or negative, because *Q* can be positive or negative

The electric potential varies according to 1 / r

Electic potential difference (ΔV) is the energy needed to move a unit charge between two points

ΔGPE = m ΔV

Work done to move a unit charge between two points = Q ΔV

ΔPE = Q ΔV

99	be able to draw and interpret diagrams using field lines and equipotentials to describe radial and uniform electric fields

Electric field lines

Field lines are used to represent the **direction** and **magnitude** of an electric field

In an electric field, field lines are always directed from the positive charge to the negative charge

<table>
<tr><th>Uniform Field</th><th>Radial Field</th></tr>
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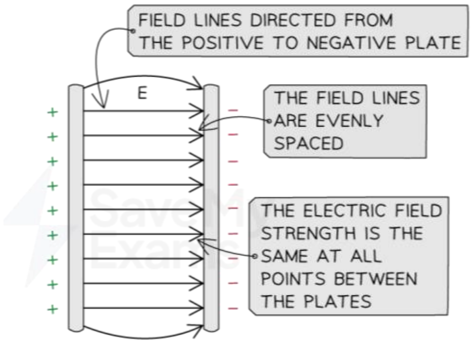

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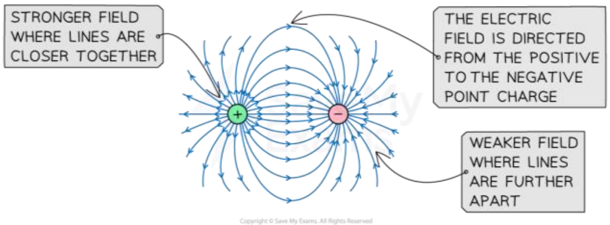

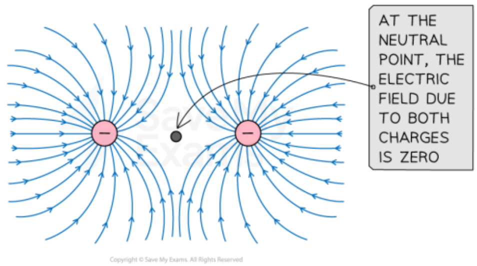

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<tr><td>
- The field lines are equally spaced at all points
- Electric field strength is constant at all points in the field
- The force acting on a test charge has the same magnitude and direction at all points in the field
</td><td>
- The field lines are equally spaced as they exit the surface of the charge but the distance between them increases with distance
- Electric field strength decreases with distance from the charge producing the field
- The magnitude of the force acting on a test charge decreases with distance
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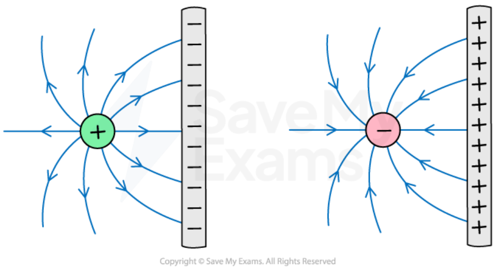
</table>

Electric field between a point charge and parallel plate

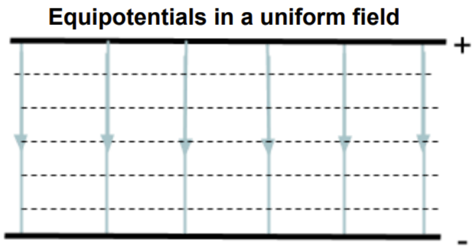
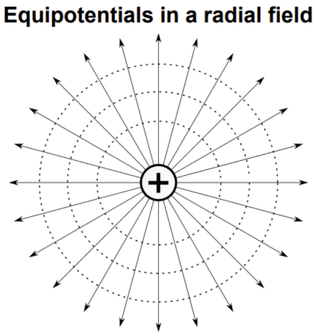


Equipotential diagrams

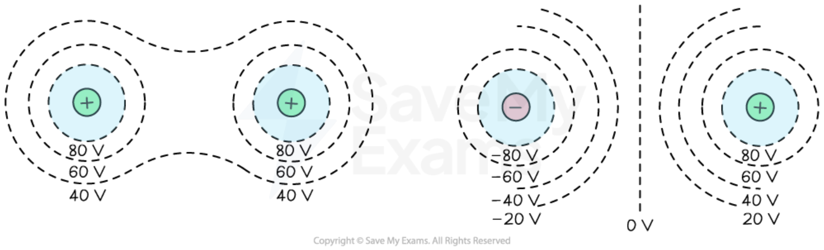
Equipotential lines (2D) and surfaces (3D) join together points that have the same electric potential, therefore when a charge moves along an equipotential surface, no work is done

These are always:

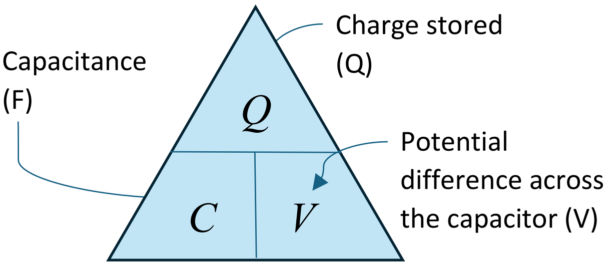
- *perpendicular* to the electric field lines in both radial and uniform fields
- represented *by dotted lines* (unlike field lines, which are solid lines with arrows)
- an equal *distance* from the source charge

Uniform Field	Radial Field
	
○ horizontal straight lines ○ parallel ○ equally spaced Equally spaced equipotential lines indicate a region of *constant electric field strength* (due to constant potential gradient)	○ are concentric circles around the charge ○ become progressively further apart with distance

Equipotential surface for multiple charges



100 understand that capacitance is defined as $C = \dfrac{Q}{V}$ and be able to use this equation



Capacitance (F) is *the charge stored by a capacitor per unit potential difference* (in Farad, F)

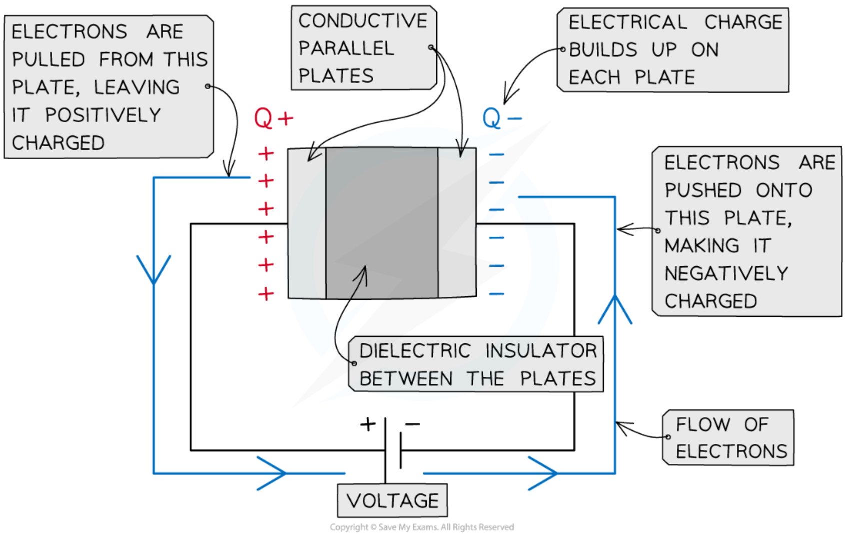
Capacitors are electrical devices used to store energy in electronic circuits, commonly for a backup release of energy if the power fails

- Capacitors do this by storing electric **charge**, which creates a build up of electric **potential energy**
- They are made in the form of two conductive **metal plates** connected to a voltage supply (parallel plate capacitor)
- They have the symbol: 

101	be able to use the equation $W = ½\ QV$ for the energy stored by a capacitor, be able to derive the equation from the area under a graph of potential difference against charge stored and be able to derive and use the equations $W = ½\ CV^2$ and $W = \frac{½\ Q^2}{C}$

Energy Stored by a Capacitor

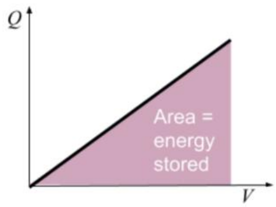
- When charging a capacitor, the power supply 'pushes' electrons to one of the metal plates and, therefore does work on the electrons and electrical energy becomes stored on the plates
- The power supply 'pulls' electrons off of the other metal plate, attracting them to the positive terminal, producing a potential difference across the capacitor
- Hence, in this way, charge is 'stored' by the capacitor
- Gradually, this stored charge builds up and greater amount of work must be done to increase the charge on the negative plate
- Hence, the potential difference across the capacitor increases as the amount of charge increases



Electrical energy stored by a capacitor (W)
= Area under graph of Charge against Potential difference

As potential difference is directly proportional to charge, this graph forms a straight line through the origin, meaning the area underneath it is a right angle triangle

so: $W = ½\ QV$



Formula derivations for W = ½ QV

102	be able to draw and interpret charge and discharge curves for resistor capacitor circuits and understand the significance of the time constant *RC*

Charging & Discharging a capacitor

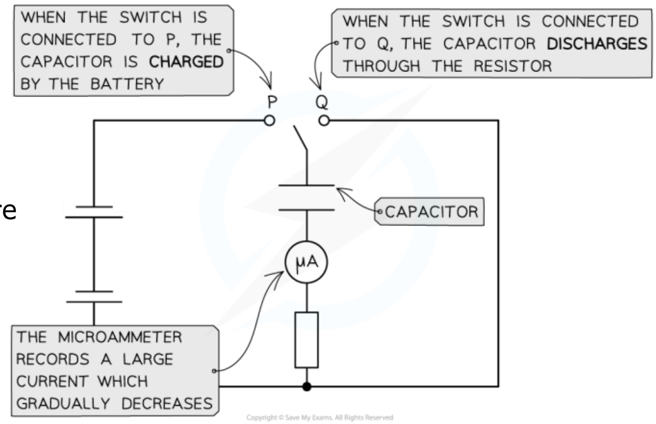
To charge a capacitor you must connect it in a circuit with a power supply and resistor

To discharge a capacitor through a resistor, you must connect it to a closed circuit with just a resistor with no power supply

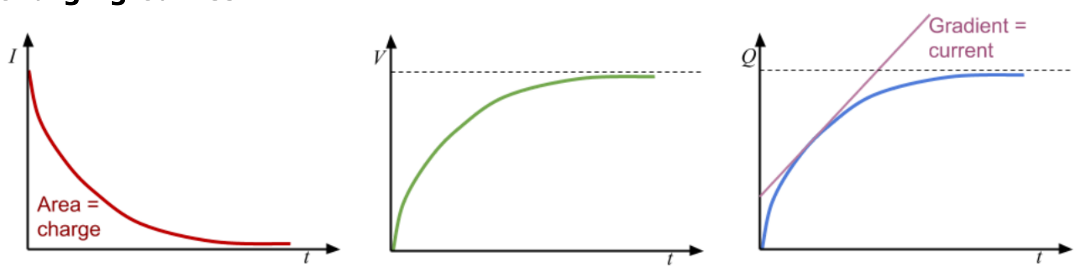
- Charging and discharging is commonly achieved by moving a switch that connects the capacitor between a power supply and a resistor

You could use a data logger to measure the values of potential difference and current to plot a graph of *voltage and current against time*

As Q = It, you can also draw a graph of *charge against time* by measuring the area under the current-time graph

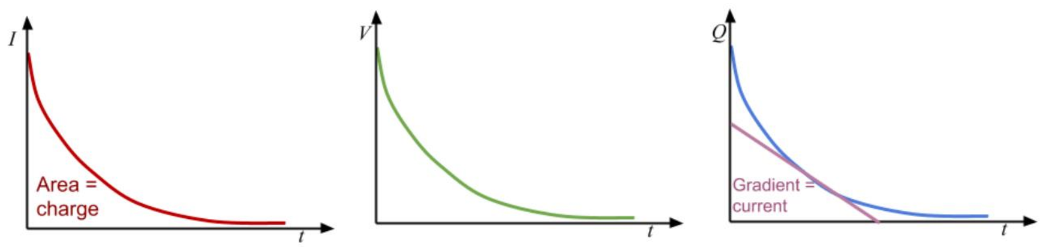


Charging Curves



- Once the capacitor is connected to a power supply, current starts to flow and negative charge builds up on the plate connected to the negative terminal
- On the opposite plate, electrons are repelled by the negative charge building up on the initial plate, so these electrons move to the positive terminal and an equal but opposite charge is formed on each plate, creating a potential difference
- As the charge across the plates increases, the potential difference increases but the electron flow decreases due to the force of electrostatic repulsion also increasing from the electrons already on the plate
- Therefore, current decreases and eventually reaches zero

Discharging Curves



When the capacitor is discharging the current flows in the opposite direction, and the current, charge and potential difference across the capacitor will all fall exponentially, meaning it will take the same amount of time for each of the values to halve

Time Constant RC

- For a **discharging** capacitor, time constant is:

The time taken for the charge, current or potential difference of a discharging capacitor to decrease to 37% (or 1/e) of its original value

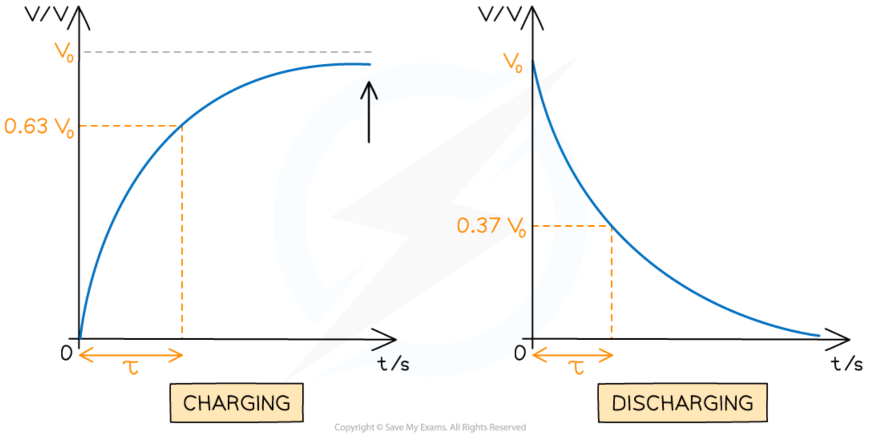
- For a **charging** capacitor:

The time taken for the charge or potential difference of a charging capacitor

to increase to 63% (or 1 – 1/e) of its maximum value

In other words, time constant (RC) is the time taken to:

- **Discharge a capacitor** to $\frac{1}{e} \approx 0.37$ **of its initial value** (of charge, current or voltage)
- **Charge a capacitor** to $(1 - \frac{1}{e}) \approx 0.63$ **of its initial value** (of charge or voltage)



When charging $V = V_0 - V_0 e^{-t/RC}$ and when discharging $V = V_0 e^{-t/RC}$

103 **CORE PRACTICAL 11: Use an oscilloscope or data logger to display and analyse the potential difference (p.d.) across a capacitor as it charges and discharges through a resistor**

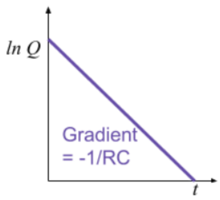
104 be able to use the equation $Q = Q_0 e^{-t/RC}$ and derive and use related equations for exponential discharge in a resistor-capacitor circuit, $I = I_0 e^{-t/RC}$, and $V = V_0 e^{-t/RC}$ and the corresponding log equations $\ln Q = \ln Q_0 - \frac{t}{RC}$, $\ln I = \ln I_0 - \frac{t}{RC}$ and $\ln V = \ln V_0 - \frac{t}{RC}$

Since the graph of Q against t follows an exponential curve for capacitor discharging, the equation to calculate the value of charge at a certain point in time involves an exponential function: $Q = Q_0 e^{-t/RC}$

From the above equation, you can derive related equations for calculating the current and potential difference of a discharging capacitor

To derive the equation for calculating the potential difference
To derive the equation for calculating the current

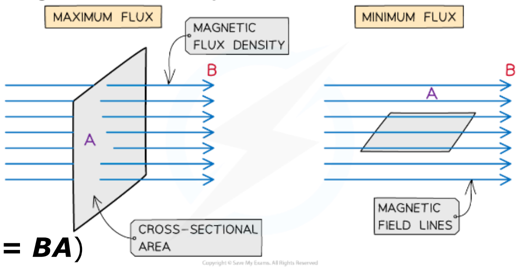
If you plot a graph of ln(Q) against t, the **gradient of this graph is** $\frac{-1}{RC}$, therefore $RC = \frac{-1}{gradient}$.



105 | understand and use the terms *magnetic flux density B, flux φ* and *flux linkage Nφ*

Magnetic flux density (B)
- is a measure of the strength of a magnetic field (measured in the Tesla, T)
- It is the density of the magnetic field lines at that point

Magnetic flux (ϕ)
- is a value which describes the magnetic field or magnetic field lines passing through a given area (measured in Webers, Wb)
- The amount of magnetic flux through a rotating coil will vary as the coil rotates in the magnetic field
  - Maximum when field lines are perpendicular to the coil area
  - Minimum when field lines are parallel to the coil area
- Calculated by finding the product of the magnetic flux density and the cross-sectional area perpendicular to the field (***Φ = BA***)



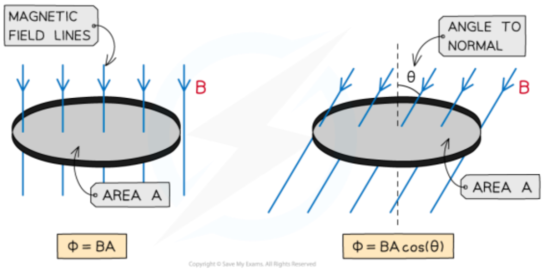
What if Magnetic Flux is not perpendicular to the Area?

Well, then the component of the magnetic flux density *B* perpendicular to the area is taken

The equation then becomes:

$$\Phi = BA\cos(\theta)$$

Where θ = angle between magnetic field lines and the normal line



Magnetic flux linkage (Nϕ)
- is the product of magnetic flux and the number of turns N, of a coil (is measured in Weber turns, Wb turns)
- Calculated by ***NΦ = NBA***
- An e.m.f is induced in a circuit when there is a change in magnetic flux linkage with respect to time and so this means an e.m.f is induced when there is:
  - A changing magnetic flux density *B*
  - A changing cross-sectional area *A*
  - A change in angle *θ*

106 | be able to use the equation $F = Bqv\sin\theta$ and apply Fleming's left-hand rule to charged particles moving in a magnetic field

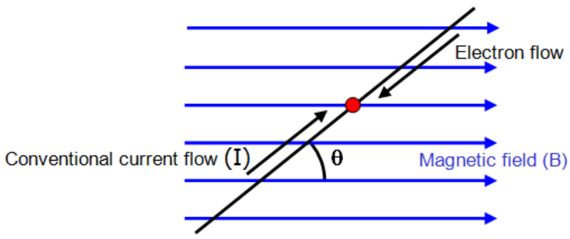
Charged particles moving in a magnetic field

A force acts on charged particles moving in a magnetic field, this is why a force is exerted on a current-carrying wire in a magnetic field, because it contains moving electrons, which are negatively charged particles

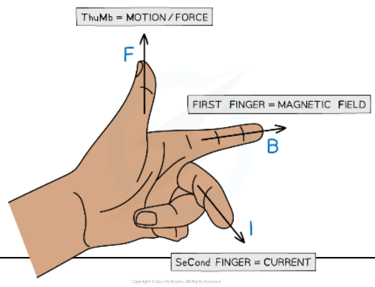
To calculate this force:

$$F = Bqv\sin\theta$$

Where θ is the angle between the velocity of the particle and the direction of the magnetic field



To find the direction of the force exerted on a charged particle you can use Fleming's left-hand rule:



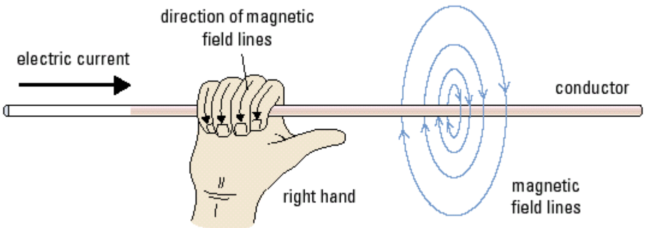
To find the direction of motion/force exerted on a charged particle you can use Fleming's left hand rule, using the second finger as the direction of travel, however <u>*if the charge on the particle is negative*</u>, reverse the direction of your second finger, because the seCond finger represents Conventional Current, which flows from positive to negative

<table>
<tr><td></td><td>The force exerted is always perpendicular to the motion of travel, which causes charged particles to follow a circular path when in a magnetic field, because the force induced by the magnetic field acts as a centripetal force</td></tr>
<tr><td>107</td><td>be able to use the equation $F = BIl \sin\theta$ and apply Fleming's left-hand rule to current carrying conductors in a magnetic field</td></tr>
<tr><td></td><td>

Current carrying conductors in a magnetic field

When current passes through a wire, a magnetic field is induced - this is true for any long, straight current-carrying conductor

The field lines of the induced magnetic field form concentric rings around the wire



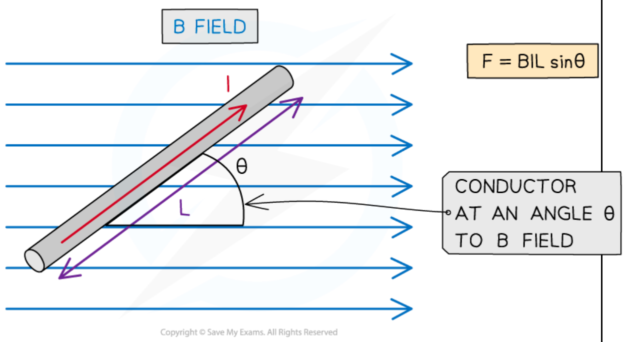
When a current-carrying wire is placed in magnetic field, a force is exerted on the wire

To find the magnitude of the force: $$F = BIl \sin\theta$$

Where l is length of current-carrying conductor

A current carrying conductor (wire) will experience **maximum** magnetic force if the current through it is **perpendicular** to the direction of the magnetic field lines

A current carrying conductor (wire) will experience **minimum** magnetic force if the current through it is **parallel** to the direction of the magnetic field lines



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<tr><td>108</td><td>understand the factors affecting the e.m.f. induced in a coil when there is relative motion between the coil and a permanent magnet</td></tr>
<tr><td></td><td>

Induction of e.m.f in a coil through relative motion between the coil and a permanent magnet

- When the coil or any conductor moves relative to a magnetic field created by two permanent magnets, there is a change in magnetic flux Φ or magnetic flux linkage $N\Phi$ with the coil
- Hence, an e.m.f. is induced in the coil
- If the coil is a complete and closed circuit, a current will be induced in the coil or the conductor moving
- This is known as electromagnetic induction and is defined as:
"The process in which an e.m.f is induced in a closed circuit due to changes in magnetic flux (linkage)"
- This process can be seen when the permanent magnet is moved relative to the conductor OR when a conductor cuts through a magnetic field OR when the coil of conductor is rotated in a magnetic field
- Electromagnetic induction is used in:
  - Electrical generators which convert mechanical energy to electrical energy
  - Transformers which are used in electrical power transmission

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These will increase induced emf:
- Moving the magnet faster through the coil
- Adding more turns to the coil
- Increasing the strength of the bar magnet

Factors affecting the induced e.m.f.

Faraday's law can be expressed using the following equation:

$$\varepsilon = N \frac{\Delta\Phi}{\Delta t}$$

Where **ε** is magnitude of induced emf, and **N** $\frac{\Delta\Phi}{\Delta t}$ is rate of change of flux linkage.

Using the equation for **Faraday's law** (above), you can see that the factors affecting the emf induced in a coil when there is relative motion between the coil and a permanent magnet are:

- The **number of turns in the coil (N)** -
  - This is directly proportional to the induced emf
- The **magnetic flux density (B)** of the field created by the permanent magnet -
  - This is directly proportional to the induced emf (as $\Phi = BA$)
- The **area of the cross section (A)** of the coil -
  - This is directly proportional to the induced emf (as $\Phi = BA$)
- The **time taken (t)** for the motion -
  - This is **inversely** proportional to the induced emf

When the coil is being rotated, increasing the coil's frequency of rotation increases:
- The frequency of the alternating voltage induced
- The amplitude of the alternating voltage induced

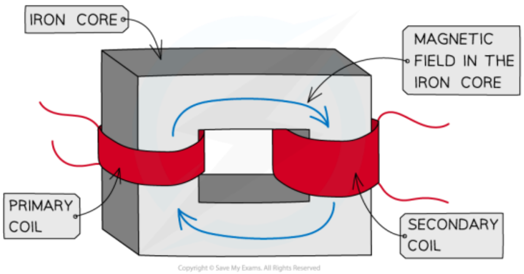
109 understand the factors affecting the e.m.f. induced in a coil when there is a change of current in another coil linked with this coil

Induced e.m.f. between Linked Coils (Transformers)

- An **e.m.f** can be induced in a coil when there is a change of current in another coil linked with this coil

A transformer changes high alternating voltages at low current to low alternating voltage at high current, and vice versa

- In a transformer, primary and secondary coils are wound around a soft iron core
- The soft iron core is necessary because it creates **flux linkage** between the primary and secondary coils
- Soft iron is used because it can easily be magnetised and demagnetized



- In the primary coil, an alternating current is supplied which produces an alternating voltage in it
- This creates an **alternating magnetic field** inside the iron core and therefore a changing **magnetic flux linkage**
- A changing magnetic field passes through to the secondary coil through iron core
- This results in a changing magnetic flux linkage in the secondary coil and from Faraday's Law, an **e.m.f is induced**
- An e.m.f produces an alternating output voltage from the secondary coil
- The output alternating voltage is at the **same** frequency as the input voltage

110	understand how to use Faraday's law to determine the magnitude of an induced e.m.f. and be able to use the equation that combines Faraday's and Lenz's laws $\varepsilon = \frac{-\mathrm{d}(N\varphi)}{dt}$
	Faraday's Law - It states that: **"The magnitude of the induced e.m.f is directly proportional to the rate of change of magnetic flux linkage"** As an equation, it shows that: $\varepsilon = N \frac{\Delta\Phi}{\Delta t}$ Where ε = induced e.m.f (V), $\Delta(N\phi)$ = change in flux linkage (Wb turns), Δt = time interval (s) **Lenz's Law** - Lenz's law states that: **"The direction of the induced e.m.f. is such as to oppose the change (motion) causing it"** - Lenz's Law is used to predict the direction of an induced e.m.f in a coil or wire **Combining Lenz's Law and Faraday's Law** $$\mathscr{E} = \frac{-\mathrm{d}(N\phi)}{\mathrm{d}t}$$ - The **negative sign** represents Lenz's Law as it shows the direction of the induced e.m.f is such that it acts in the **opposite direction** to oppose the changing flux linkage that causes it - This equation also shows that the **gradient** of the graph of magnetic flux (linkage) against time represents the **magnitude** of the induced e.m.f.